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(54) **Optical modulator**

(57) An optical modulator comprises a bi-moded fibre (2) for supporting first and second different optical transmission modes, coupled between input and output single mode fibres (1, 3). The two modes in the bi-moded fibre (2) interfere and the intensity of the radiation that passes to the single mode output fibre (3) is a function of the relative phases of the first and second modes. The bi-moded fibre (2) is electrically poled and is provided with modulating electrodes (19, 20). When a modulating voltage from a modulating source (V) is applied to the electrodes, the refractive index of the waveguide for the first transmission mode is altered relative to the refractive index of the waveguide for the second mode such as to change the phase difference between the modes at the entrance to the output fibre (3) so as to control the intensity of optical radiation that passes through the output fibre (3).

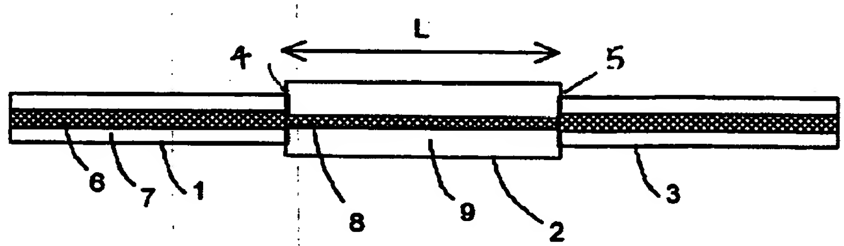


Fig. 1

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## Description

This invention relates to an optical modulator for use in waveguides such as optical fibres or planar substrate devices.

Hitherto, an optical multi-waveguide interference filter has been proposed, in which a first waveguide capable of single mode transmission, is coupled to a second waveguide capable of supporting at least two transmission modes. A third waveguide supporting a single mode is used to pick up light from the second, multimode waveguide. In use, light in a single mode passes from the first waveguide into the second waveguide where it is transmitted in two modes, which interfere with one another. By an appropriate selection of the length of the second waveguide and its optical characteristics, the interfering modes produce an amplitude peak at the entrance to the third waveguide, which shifts diametrically across the input to the third waveguide as a function of wavelength. The filter is described in detail in "An Optical Multi-waveguide Interference Filter" M. Earnshaw et al, Optics Communications 116 (1995), 339-342, 1 May 1995.

It has also been proposed to sense temperature by sensing mode-mode interference in a birefringent optical fibre, as described by W. Eickoff, Optics Letters, Vol. 6, No. 4 April 1981 pp 204-206.

Electro-optic modulation of a silica-based fibre has been proposed by T. Fujiwara et al, Electronics Letters, 30 March 1995, Vol. 31 No. 7, pp 573-575. In order to pole the fibre and provide it with an electro-optic coefficient, a voltage was applied to wires inserted into the fibre whilst irradiating it with ultraviolet radiation. Thereafter, the application of a voltage to the wires produced a phase shift for optical radiation transmitted through the fibre.

The present invention provides a different approach for producing modulation in an optical waveguide.

In accordance with the invention there is provided an optical modulator comprising: a waveguide for supporting first and second different optical transmission modes, an output for optical radiation from the waveguide, the intensity of the radiation that passes through the output being a function of the relative phases of the first and second modes at the output, and modulating means that is operable to alter selectively the refractive index of the waveguide for the first transmission mode relative to the refractive index of the waveguide for the second mode such as to change the phase difference between the modes at the output and thereby control the intensity of optical radiation that passes through the output.

Stated differently, the invention provides an optical modulator comprising: a waveguide for supporting first and second different optical transmission modes, an output for optical radiation from the waveguide, the intensity of the radiation that passes through the output being a function of the relative phases of the first and second modes at the output, and modulating means that is operable to apply a field to the waveguide so as to change the phase difference between the modes at the output and thereby control the intensity of optical radiation that passes through the output.

The waveguide may be formed of electro-optic material and the modulating means may comprise means for applying an electric field to the material. The electro-optic material may comprise electrically poled material, which may be thermally poled.

The modulator according to the invention may be formed in an optical fibre, such as silica-based fibre, which has been thermally poled. The fibre may include electrode means running along the length thereof to permit a modulating voltage to be applied.

A modulator according to the invention may also be embodied in a planar waveguide device.

The waveguide may be formed of semiconductor material, with the modulating means being operative to inject carriers therein to produce the refractive index alteration. The modulating means may comprise a source of optical radiation.

In order that the invention may be more fully understood embodiments thereof will now be described by way of example with reference to the accompanying drawings, in which:

Figure 1 is a schematic cross sectional view of a fibre modulator in accordance with the invention;
Figure 2 is a schematic illustration of the fibre modulator connected to a laser source and an optical detector
Figure 3 is a cross sectional view through the fibre 2 shown in Figures 1 and 2;
Figure 4 is a schematic plan view of a planar optical waveguide device incorporating a modulator according to the invention; and
Figure 5 is a schematic cross section taken along the line A-A' of Figure 4.

Referring to Figure 1, an optical fibre arrangement including a modulator according to the invention, is shown. The arrangement comprises a first, single mode fibre 1, a second, dual mode fibre 2 and a third length of fibre 3, which operates in single mode. The fibres 1 and 3 are fusion butt-jointed to opposite ends of the fibre 2, by means of fusion splices 4, 5.

The fibres 1, 3 are conventional single mode fibres as used for optical telecommunications. They typically comprise silica based fibres with a Ge/B doped core 6, surrounded by a $SiO_2$ cladding 7. Typically, the core diameter is 8 μm and the exterior cladding diameter is 125 μm. By way of example, the refractive index of the cladding $n_{cladding}$ to light at 1550

nm is approximately 1.45 and the difference between the refractive indices of the core $n_{core}$ and the cladding $n_{cladding}$, $\Delta n = n_{core} - n_{cladding} = 4.5 \times 10^{-3}$.

The second fibre 2 includes a core 8 surrounded by a cladding 9 and is of the same general construction as the single mode fibres 1 and 3 but is capable of supporting multiple transmission modes. As is known in the art, multiple mode transmission can be achieved when a fibre parameter υ known as the normalised frequency, exceeds a particular value, where

$$v = \frac{2\pi\alpha}{\lambda}\sqrt{(n_{core}^{2} - n_{cladding}^{2})}$$

where $a$ is the radius of the core. Assuming that the refractive index $n \simeq n_{core} \simeq n_{cladding}$, and $\Delta n = n_{core} - n_{cladding}$, then this can be expressed as:

$$v \simeq \frac{2\pi a}{\lambda}\sqrt{2n\Delta n} \qquad (1)$$

Typically, multimode operation can occur if υ exceeds a value of 2.405. From equation (1), it can be seen that this can be achieved by making an appropriate selection the of values of Δn and the core radius $a$. Thus, by a suitable selection of fibre parameters, the fibres 1 and 3 have a v value of less than 2.405 and the fibre 2 has a value v that is greater than 2.405.

In the following example, the core 8 of the multimode fibre 2 has a radius $a$ that is less than that of the single mode fibres 1, 3, as will be described in more detail later, together with an appropriate value of Δn, higher than that of the single mode fibres 1, 3, in order to satisfy the conditions required to support dual mode transmission. The fibre 2 may be formed of germania doped silica, with or without boron sodium or defect rich dopant such as cerium. The fibre in this example supports the LP 01 and LP 11 transmission modes. A typical length L for the fibre 2 is 2.4 cm. The length of the fibres 1, 3 is not critical.

Referring to Figure 2, the fibre arrangement of Figure 1 is connected at one end to a laser 10 operative in the 1500 nm telecommunications band, which injects optical radiation into the core 6 of fibre 1. Light emanating from the core 6 of fibre 3 is focused by a lens 11 onto an optical detector 12. The optical fibre 2 operates as a modulator as will now be explained in more detail. Figure 3 illustrates a transverse cross section of the fibre 2 and generally corresponds to the optical fibre shown in Figure 9 of our co-pending PCT/GB97/00266 filed on 30 January 1997 (which designates EPC). When viewed in cross section, the fibre has a relatively broad dimension $b$ and a relatively narrow dimension $w$ in a second direction normal to the first direction. Two recesses 13, 14 have a depth $d$ extend from planar surface regions 15, 16 towards the core 8 along the length of the fibre. The planar surface regions 15, 16 are connected by curved, cylindrical surface regions 17, 18 that extend along the length of the fibre. Typically, the breadth $b$ is 250 μm, the width $w$ is 100 μm and the depth of the recesses is of the order 30 μm. The bottom of the recesses 13, 14 are spaced from the core by 9-15 μm. The diameter of the core 8 is typically 4 - 8 μm and in this example is 6 μm. The value of Δn for the fibre 2 is 0.012 and $n_{cladding}$ is 1.45.

The recesses are coated with electrodes 19, 20, formed by evaporation of a metallic source and deposition of the vapour in the recesses. The electrodes 19, 20 may be formed of gold. The recesses thereafter are filled with an electrically insulating material such as silicon rubber 21 so as to protect the fibre from glass/air dielectric breakdown and flash-over. As shown in Figure 2, external leads 22, 23 are connected to the electrodes 19, 20 respectively. For further details of the fibre structure, including details of its manufacture and the dopant concentrations used reference is directed to PCT/GB97/00266 the contents of which are incorporated herein by reference.

The core of fibre 2 is photosensitive to UV light. When doped with Ge or Ge and B, it is photosensitive to radiation with a wavelength of 244 nm. The material of the fibre can be poled by heating the fibre and applying an electric field between the electrodes 19, 20, whilst directing UV light at 244 nm towards the fibre. This is described in more detail in T. Fujiwara, D. Wong, Y. Zhao, S. Flemming v. Grishina and S. Poole "UV Excited Poling and Electrically Tunable Bragg Gratings in a Germo Silicate Fibre", post deadline paper OFC 1995 (Feb 1995). Further details of fibre poling methods can be found in "Phase Matched Second-Harmonic Generation by Periodic Poling of Fused Silica" R. Kashyap et al Appl. Phys. Lett. 64 (11) 14 March 1994 pp 1332-1334; "High Second-Order Non-linearities in Poled Silicate Fibres" P.G. Kazansky et al, Optics Letters, 15 May 1995, Vol. 19 No. 10 pp 701-703 and "Electro-Optic Phase Modulation in a Silica Channel Waveguide" A. C. Liu et al Optics Letters Vol. 19, No. 7 1 April 1994, pp 466-468. As a specific example, the poling voltage was applied directly to the electrodes 19, 20 and was up to 2kv over 35 μm, giving a field strength of

the order of 5 - 6 x$10^7$ v/m. Alternatively, the poling voltage may be applied to the fibre using an additional electrode on a Si wafer as described in "A Poled Electrooptic Fiber" X.C. Long et al, IEEE Photonics Technology Lett. Vol 8, No 2, February 1996, pp 227-229. The poling temperature was 260-280°C.

It has been found that after poling, when an electric voltage is applied to the electrodes 19, 20, the fibre presents a different refractive index to the LP 01 and the LP 11 transmission mode resulting in a voltage-dependent phase difference between them. As a result, the two modes interfere by an amount dependent upon the applied voltage. It has been found that by varying the applied voltage, the amplitude peak produced as a result of interference can be swept across the entrance to the single mode core of the third fibre 3 shown in Figure 1, at the butt joint 5. Thus, by varying the voltage produced by the modulated voltage source V, the intensity of light received at the optical detector 12 can be varied. Thus, the device can be used as a modulator.

A specific example of the applied voltage range, is up to 1 kv. This corresponds to a range of applied field of 0 → $10^7$ v/m. The contrast ratio achievable is of the order of 100%. The bit rate that can be achieved by means of the described example optical modulator according to the invention, is of the order of ten times greater than can be acheived with a comparable conventional lithium niobate doped optical fibre modulator and is typically > 20GHz.

Another example of the invention will now be described with reference to Figures 4 and 5. In this example of the invention, the optical waveguide is formed in a planar substrate, typically made of silicon. Details of how a silicon substrate can be processed in order to provide a doped silica waveguide as an elongate strip, surrounded by an undoped silica cladding region, is discussed in detail in our US Patent No. 5 342 478 dated 30 August 1994.

As shown in Figure 4 and 5, the device comprises a silicon substrate 24 and an elongate waveguide 25 formed on the substrate 24. As shown in the cross section of Figure 5, the substrate 24 is formed with a trench filled with thermal oxide 26 onto which a doped oxide layer is formed in order to form the core of the waveguide. The oxide layer (not shown) is plasma etched, using conventional lithographic techniques in order to form the pattern 25 shown in plan view in Figure 4. Thereafter, the region 25 is covered with an undoped oxide layer 27. The oxide layers 26 and 27 thus form a cladding around the core region 22 of the waveguide. The process may utilise the well known technique of local oxidisation of silicon (LOGOS), which is summarised in our previously mentioned US Patent No. 5 342 578.

As can be seen in Figure 4, the waveguide core 25 includes a first region $25_1$ capable of single mode operation, the second region $25_2$, wider than the first region, capable of supporting bi-moded transmission, and a third region $25_3$ capable of single mode operation. Typical transverse dimensions $x_1$, $x_2$, $x_3$ for the regions $25_{1,\,2,\,3}$ are 5 µm, 10 µm and 5 µm respectively. A typical thickness for the region 25 is of the order of 6 µm. The bi-moded region $25_2$ is thus wider than the single moded regions $25_{1,\,3}$ in contrast to the previously described fibre configuration of Figure 1. In the device of Figure 4, the value of the refractive index difference $\Delta n$ between the core and the cladding is the same for the bi-moded and single moded regions in order to simplify construction of the planar device, and so in order to satisfy the condition of equation (1) for bi-moded operation, the core dimension $x_2$ (corresponding to $2a$ in equation (1)) is made greater than the dimensions $x_1$, $x_3$. A typical value for $\Delta n$ is 5 x $10^{-3}$ and a typical approximate value of $n_{cladding}$ is 1.450. An example of the core dopant used is germania to a concentration of approximately 3 mole percent. The single moded regions $25_1$, $25_3$ are offset from the longitudinal centreline $y$ of the core 25, in the manner described by Earnshaw et al, ***supra***.

A metallisation layer 28, formed by a known evaporative technique, overlies the waveguide in the second, bi-moded region $25_2$ of the core and a corresponding electrode 29 is formed on the underside of the substrate 24. The electrodes 28, 29 can thus be used to pole the core region $25_2$ by thermal poling and/or by UV radiation, in the manner previously explained. The electrodes 28, 29 are connected to ohmic contact pads (not shown) for connection to the leads 22, 23, shown in Figure 2 so that a modulating voltage can be applied from the source V. In use, the temperature, field strengths and voltages used for poling and modulation are substantially the same as for the embodiment of Figure 1.

Thus, in use, light from the laser 10 is directed into the first, single mode portion of the core $25_1$ from which it passes into the bi-modal region $25_2$. The two modes of propagation interfere with one another, in the manner previously described. The phase difference between the interfering modes depends on the voltage V applied to the electrodes 26, 27 in the bi-modal region $25_2$ and the interference peak which can be produced at the entrance to the third single mode region $25_3$ is shifted laterally across the width of the entrance depending on the applied voltage. As a result, the intensity of the light entering the single mode region $25_3$ depends on the applied voltage. Thus, as previously explained, the device can be used to modulate the light output that is fed to the optical detector 12.

Other devices in accordance with the invention will be apparent to those skilled in the art. For example, the waveguide can be a semiconductor device as described in "Three-wavelength device for all optical processing" R.J. Manning & D.A.O. Davies, Optics Lett. Vol 19, No 12, June 1994, pp 889-891. If the device of Figure 4 is constructed as a semiconductor waveguide, having a semiconductor core configuration corresponding to the shape shown in Figure 4, the refractive index of the core presented to the different modes in the bi-moded region $25_2$, can be selectively altered by injecting carriers by means of a modulating optical source, at a wavelength different from that of the light from laser 10, giving rise to an all-optical device.

Also, those skilled in the art will appreciate that in practice, a conventional single mode optical fibre will, to a certain

extent, support bi-modal operation. Thus, it will be possible to practise the invention in a conventional single mode fibre, by poling it and providing modulation electrodes, and forcing it into bi-moded operation. Thus the invention can be performed in a single length of fibre without the need for the butt joints shown in Figure 1.

As used herein, the term "optical radiation" includes both visible and non-visible optical radiation, such as ultraviolet and infrared.

## Claims

1. An optical modulator comprising:

   a waveguide for supporting first and second different optical transmission modes,
   an output for optical radiation from the waveguide, the intensity of the radiation that passes through the output being a function of the relative phases of the first and second modes at the output,
   and modulating means that is operable to alter selectively the refractive index of the waveguide for the first transmission mode relative to the refractive index of the waveguide for the second mode such as to change the phase difference between the modes at the output and thereby control the intensity of optical radiation that passes through the output.

2. An optical modulator comprising:

   a waveguide for supporting first and second different optical transmission modes,
   an output for optical radiation from the waveguide, the intensity of the radiation that passes through the output being a function of the relative phases of the first and second modes at the output,
   and modulating means that is operable to apply a field to the waveguide so as to change the phase difference between the modes at the output and thereby control the intensity of optical radiation that passes through the output.

3. An optical modulator according to claim 2 wherein the field is induced optically.

4. An optical modulator according to claim 2 or 3 wherein the field is induced electrically.

5. An optical modulator according to any preceding claim wherein the waveguide is formed of electro-optic material and the modulating means comprises means for applying an electric field to the material.

6. An optical modulator according to claim 5 wherein the electro-optic material comprises electrically poled material.

7. An optical modulator according to claim 6 wherein the electrically poled material is thermally poled.

8. An optical modulator according to claim 6 wherein the electrically poled material comprises thermally poled silica.

9. An optical modulator according to any preceding claim including an input to the waveguide, for feeding optical radiation into the waveguide.

10. An optical modulator according to any preceding claim wherein the waveguide comprises an optical fibre.

11. An optical modulator according to any one of claims 1 to 9 wherein the waveguide comprises a planar structure on a substrate.

12. An optical modulator according to any preceding claim wherein the waveguide has been poled using UV radiation.

13. An optical modulator according to claim 1 wherein the waveguide is formed of semiconductor material, and the modulating means is operative to inject carriers therein to produce said refractive index alteration.

14. An optical modulator according to claim 13 wherein the modulating means comprises a source of optical radiation.

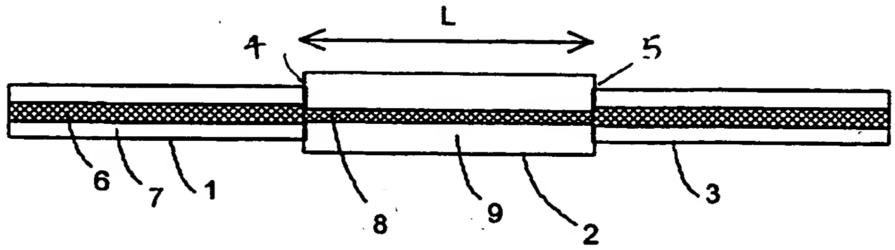


Fig. 1

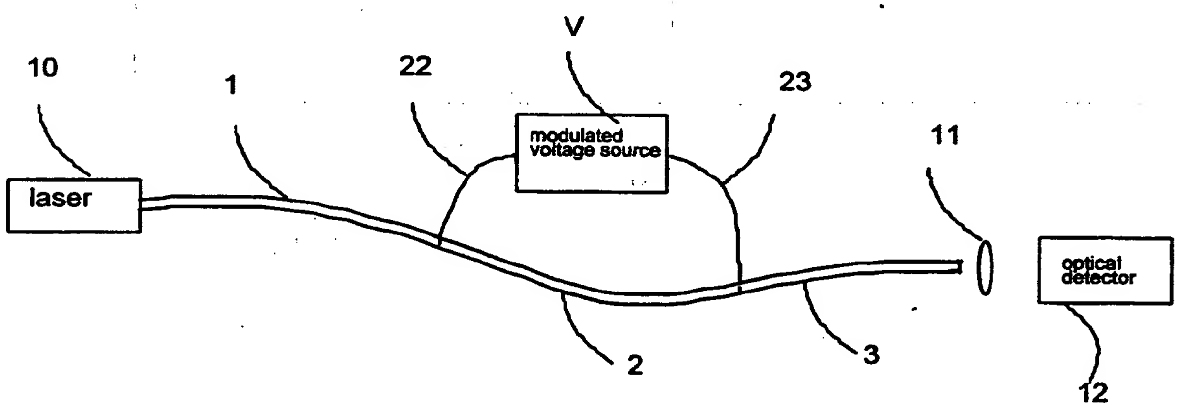


Fig. 2

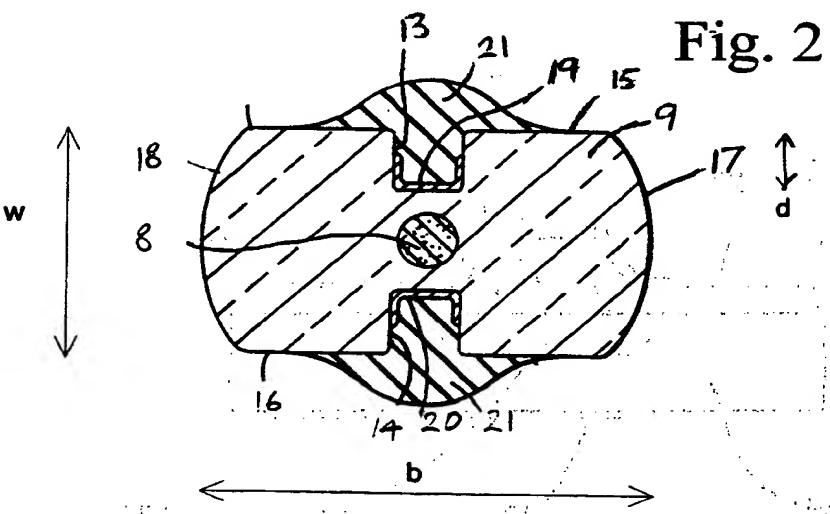


Fig. 3

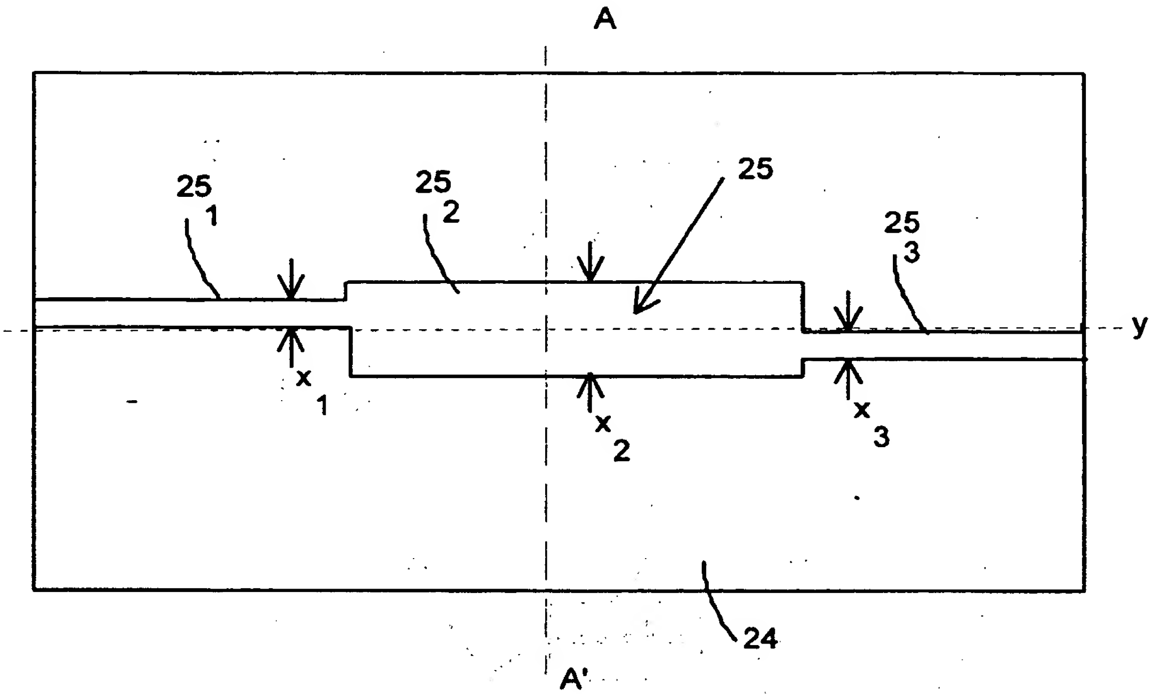


Fig.4

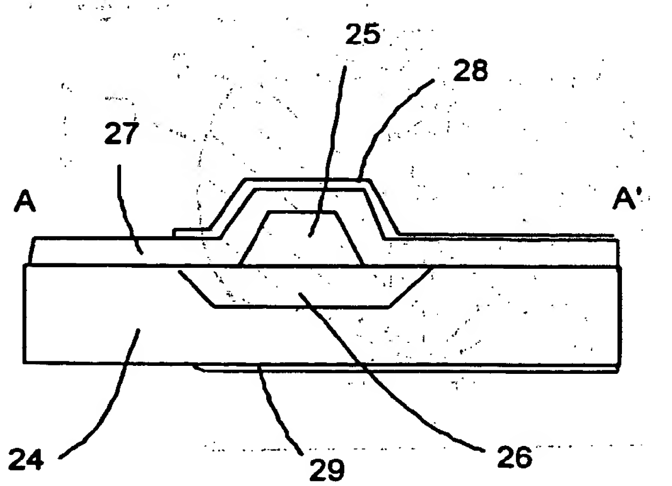


Fig. 5

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# EUROPEAN SEARCH REPORT

Application Number
EP 97 30 2524

## DOCUMENTS CONSIDERED TO BE RELEVANT

| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int.Cl.6) |
|---|---|---|---|
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The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| THE HAGUE | 4 September 1997 | Iasevoli, R |

CATEGORY OF CITED DOCUMENTS

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L : document cited for other reasons

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## DOCUMENTS CONSIDERED TO BE RELEVANT

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TECHNICAL FIELDS SEARCHED (Int.Cl.6)

The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| THE HAGUE | 4 September 1997 | Iasevoli, R |

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